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Overview of current activities in combustion instability

Space Power and Propulsion Contractor's Meeting

2 October 2015

Doug Talley, Ph.D.
Combustion Devices Branch
Air Force Research Laboratory

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Objective

- **The congressional mandate to develop a new US-built booster engine has motivated a number of programs aimed at reducing the risk of that engine developing combustion instabilities:**
  - ALREST – Advanced Liquid Rocket Engine Stability Technology
  - VISP – Virtual Injector Screening Platform.
  - SPACE - Scalable Physics-based Advanced Computational Engineering Platform.
  - CaTS – Combustion and Thrust Scaling
  - CSTD – Combustion Stability Tools Development

- **The objective of this brief is to give a broad overview of what these programs are doing.**

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ALREST

- **The Advanced Liquid Rocket Engine Stability Technology program is a three phase program to develop the next generation of combustion stability design tools.**
  - Phase 1: High fidelity model development
  - Phase 2: Multi-fidelity Tools and Methodologies
  - Phase 3: Integrated Tools Suite

- **OVERALL APPROACH: Multi-fidelity model development with progressive data validation.**

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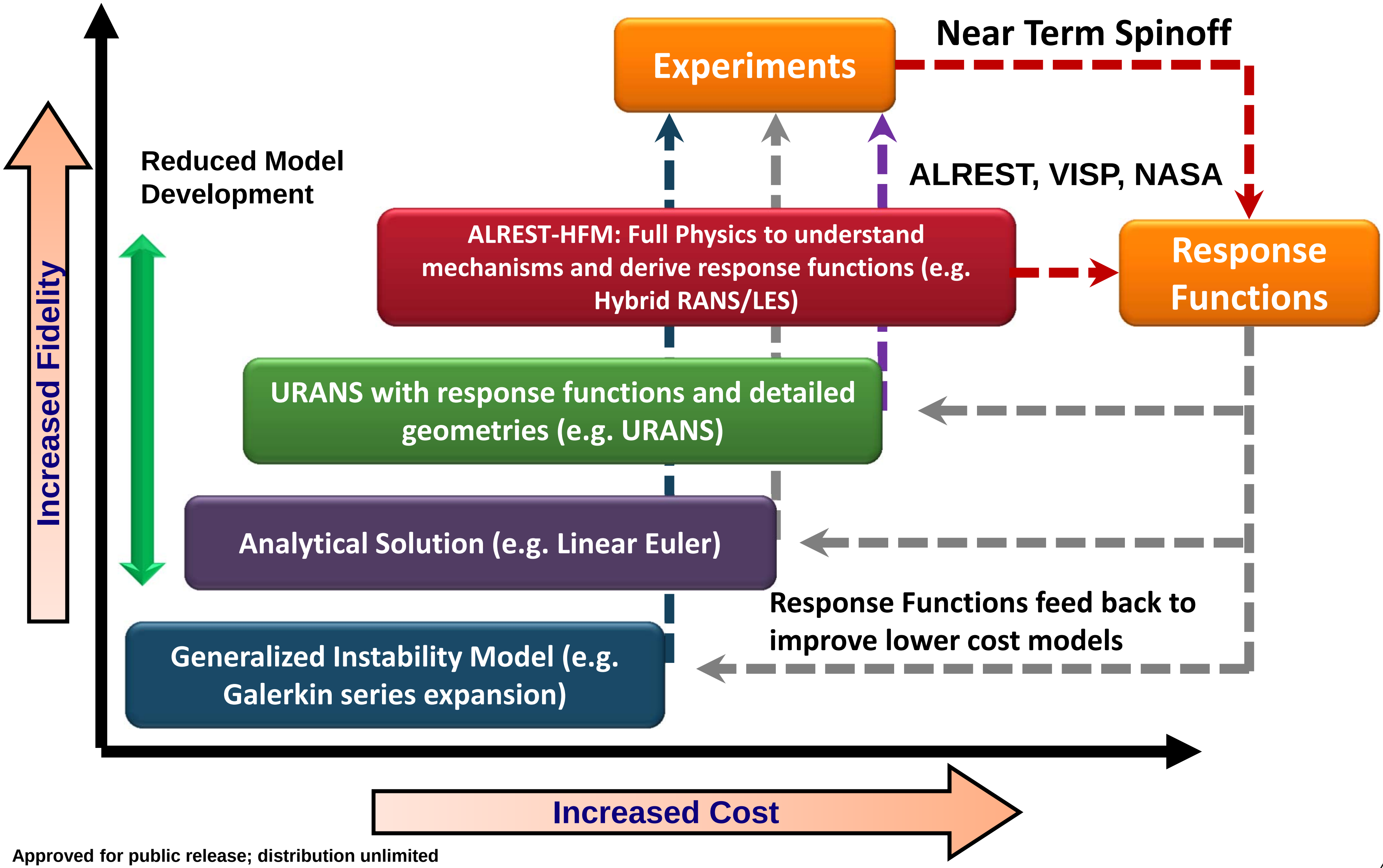
Multifidelity model development



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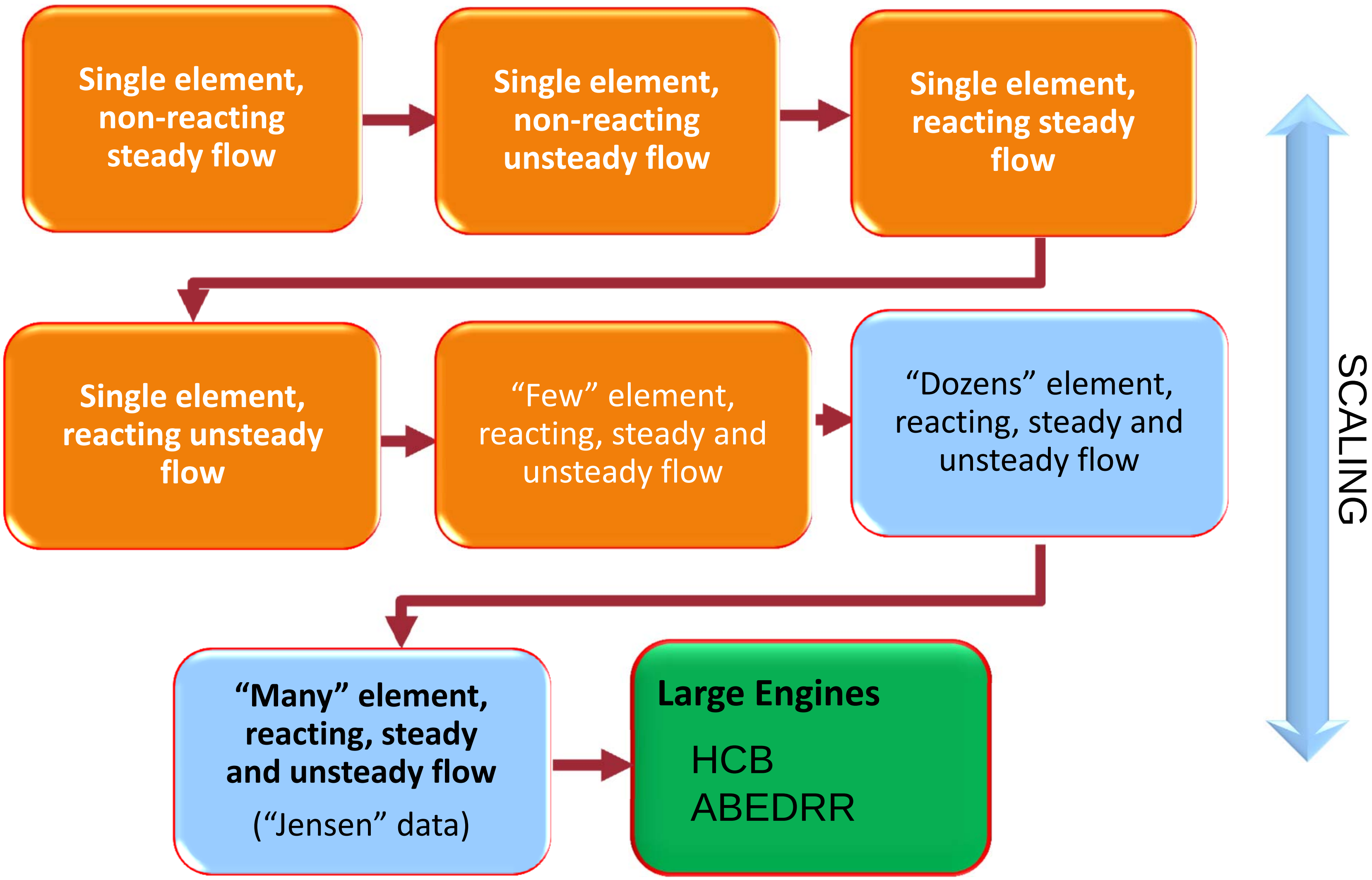
Progressive data validation



Status

- **Phase I delivered two state-of-the-art, complementary high fidelity CFD codes**
  - ALREST High Fidelity Model (AHFM)
    - Explicit, multi-block structured (fast, but difficult to grid)
  - Generalized Equation and Mesh Solver (GEMS)
    - Implicit, unstructured (easy to grid, but slow)

- **Technical effort ended on 9/30/15.**

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Virtual Injector Screening Platform (VISP)

- **VISP is a 2-year effort to accomplish:**
  - Mature the ALREST tools to a production level
    - Provide a wrapper for AHFM and GEMS
    - Add a GUI
  - Perform further validation experiments
  - Perform initial exploration of scaling methods

- **When complete, VISP will constitute a full production version of the ALREST phase I codes.**

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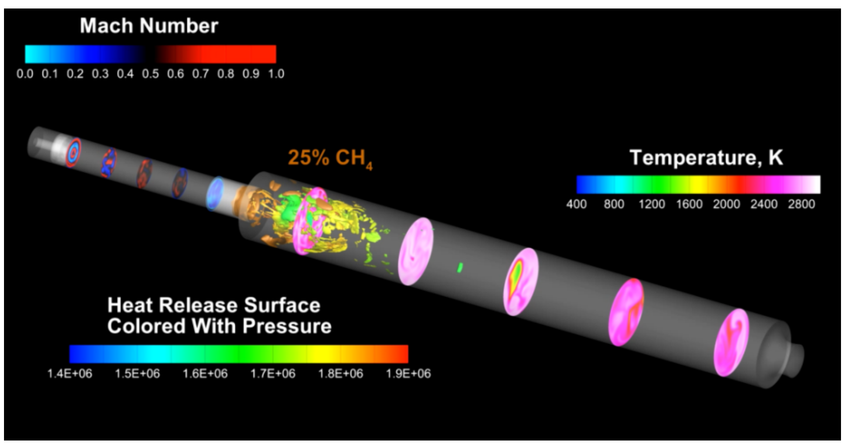
Validation Status

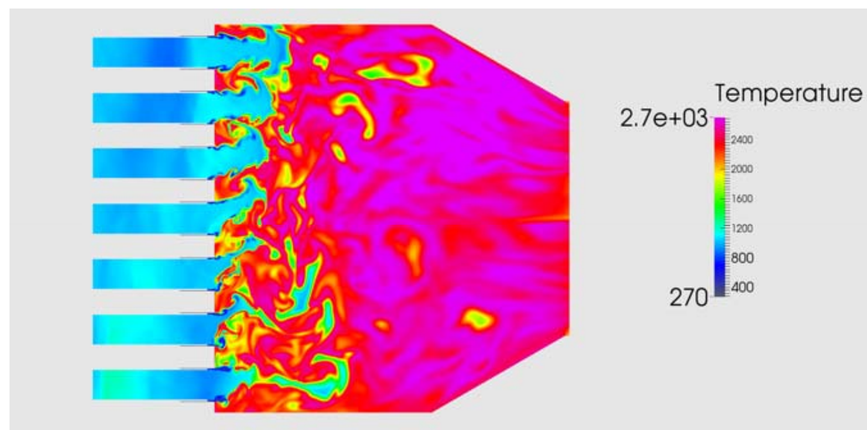
- **Validations nearly complete through case 3 and started on case 4.**
  - **Case 4 and beyond will be continued as a part of VISP and CSTD**

Case 3 Longitudinal Experiment



Controllable amplitude

Case 4 Transverse Experiment



Contains 7 injectors from the longitudinal experiment

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SPACE

- **Scalable Physics-based Advanced Computational Engineering platform**
- **SPACE is a software applications project funded by the High Performance Computing Modernization Office (HPCMO) to install new technology in a *next generation* high fidelity code**
  - Cartesian codes are 10x faster than unstructured
  - Fifth-order accuracy means 10x fewer grid points
  - Adaptive mesh puts grid refinement where needed
  - Adaptive physics can be tailored to combustion
- **If SPACE is successful, VISP will eventually migrate to SPACE**

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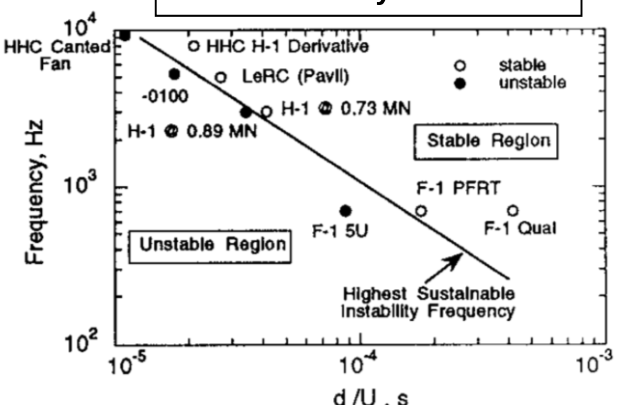
CaTS – Combustion and Thrust Scaling

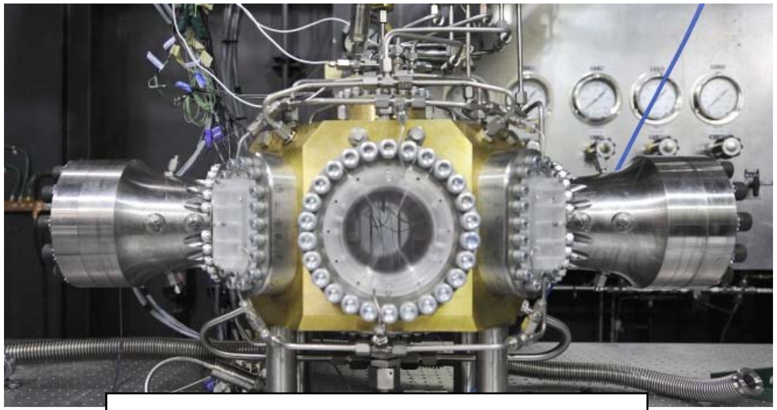
Objectives: Reduce risk of instability at full scale testing – Leverage existing tools to determine what judicious subscale testing and analysis should be done prior to full scale

Tasks *(2 year effort, ended 9/30/15):*

1. *Develop injector selection criteria for ORSC engine*
2. *Critically evaluate existing stability scaling methods*
3. *Construct an initial scaling methodology based on evaluation & SOTA knowledge*
4. *Forced flame response experiment kerosene upgrade and demonstration*

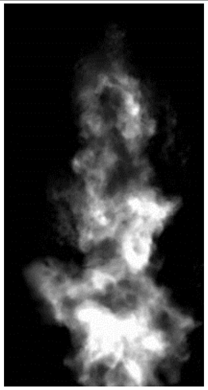
Hewitt Stability Correlation





Stability Lab Hot Fire Chamber

H2/O2 Reacting Coaxial Jet



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Combustion Stability Tool Development (CSTD)

Goal: Vastly improve U.S. ability to predict and avoid liquid rocket engine combustion stability problems

Approach: 1) Develop a SOA combustion stability software package called Stable Combustion of Rocket engines (SCORE)

2) Leverage existing and new tools to determine what judicious subscale testing and analysis should be done prior to full scale testing to decrease the risk of combustion instability

AF - SMC // Aerospace Corp *(CSTD Lead)*
Program Management & Integration

- NASA Marshall Space Flight Center (MSFC)
- Air Force Research Lab (AFRL)

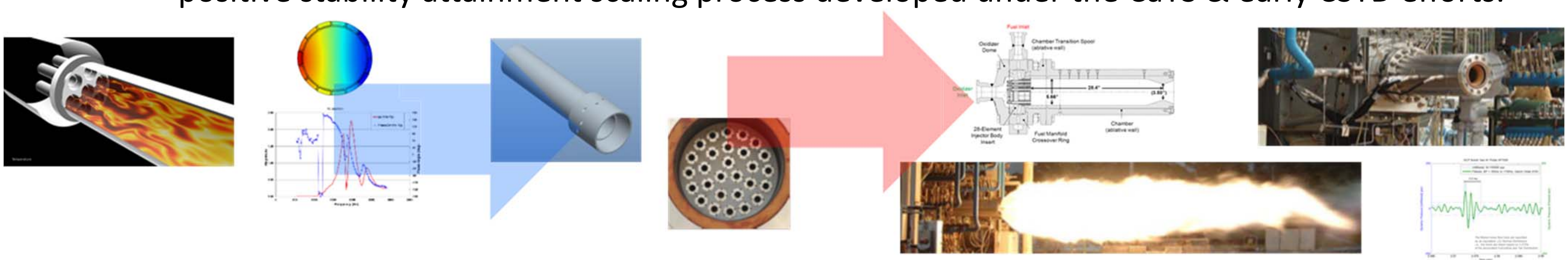
Focus: Methodology

- Georgia Tech
- Purdue

Focus: Design Tools (SCORE)

AFRL Tasks: 1) Refine ORSC main chamber single element design methodology in support of CSTD tool development by using AFRL single element hot fire testing & MSFC simulation / analysis tools to answer fundamental questions on single element design features

2) Develop multi-element experiments (~ 10 and 40 Klbf Thrust) that tests and validates the positive stability attainment scaling process developed under the CaTS & early CSTD efforts.



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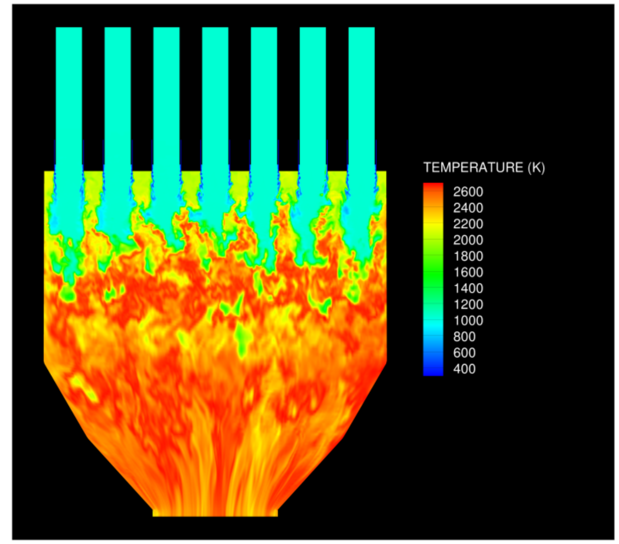
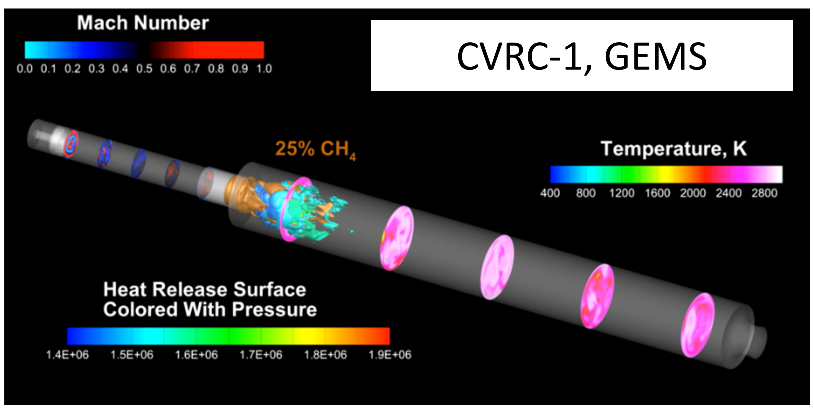
High-Fidelity Modeling

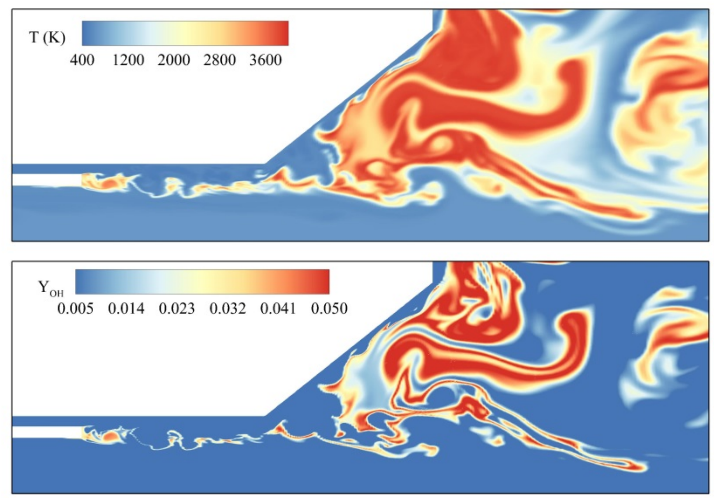
- **High-fidelity modeling is an important part of methodology**
  - All CSTD tests will be accompanied by high-fidelity simulations
    - Helps to analyze the physics and explain the results
    - Guide development of design tools



TIC-1, ALREST-HFM

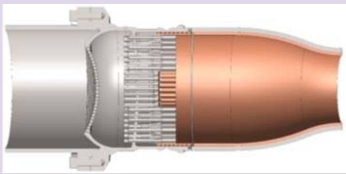


CVRC-1, GEMS

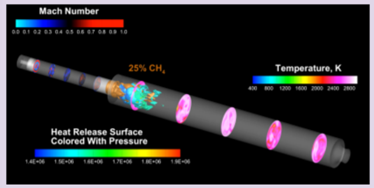


GCSC Injector, Vigor's Code

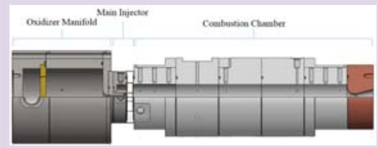
Experimental Datasets



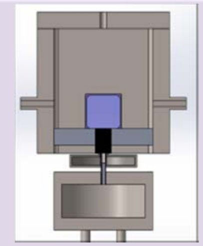
GT/ Acoustics
CSTD



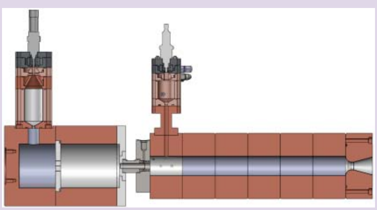
Purdue/ CVRC
CUIP



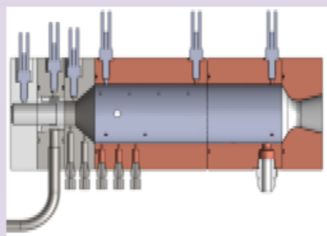
Purdue/ DVRC-1
NESC



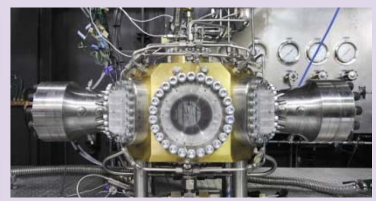
GT/ Methane
CSTD



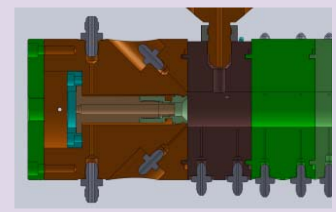
Purdue/ DVRC-2
VISP



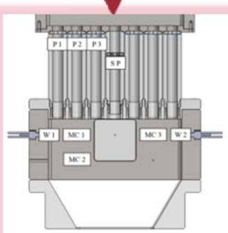
Purdue/ LS
CSTD



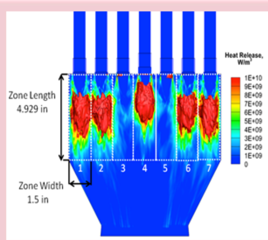
AFRL/ SL
CSTD



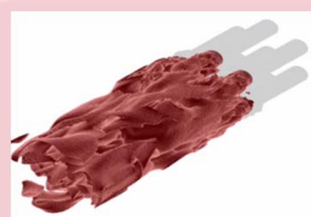
AFRL/ EC1
In-House / CSTD



Purdue/ TIC 1
AFRL



Purdue/ TIC 2
VISP / CSTD



AFRL-MSFC/ SSME
CSTD

MSFC/ LSME
CSTD

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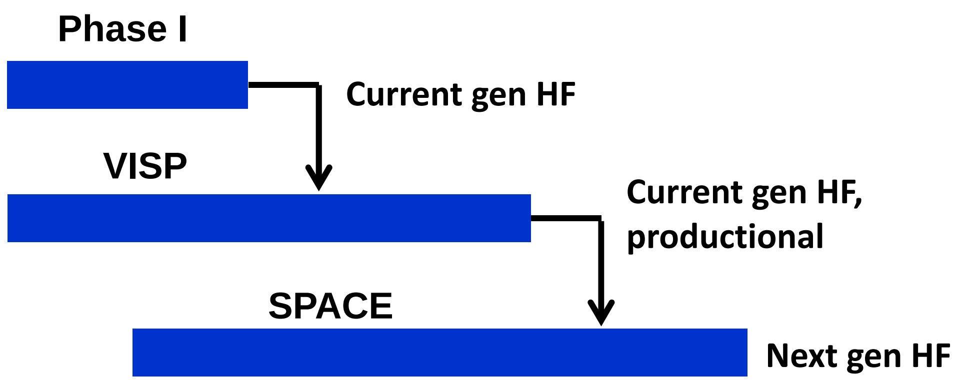
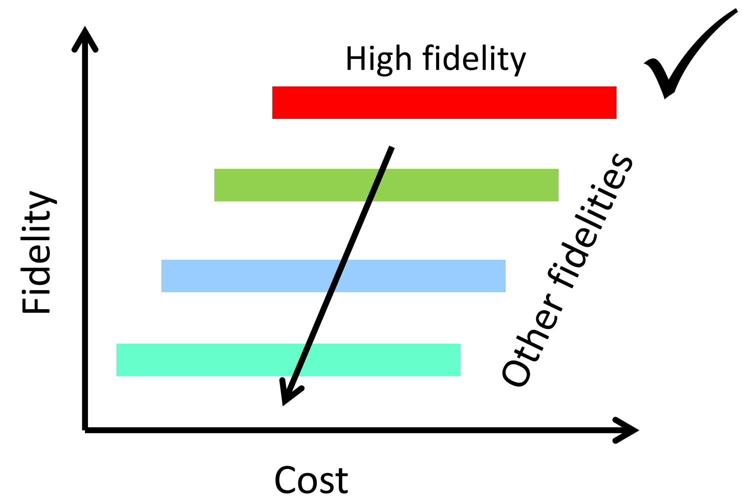
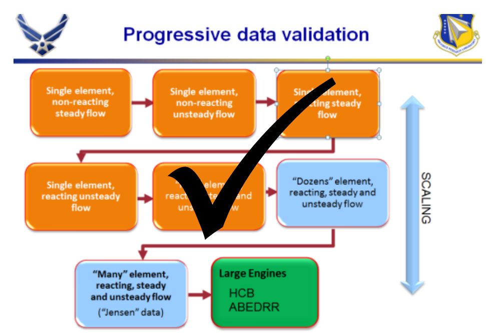
ALREST phase II





ALREST phase II

Multifidelity Tools and Methodologies



Experiments

Objective and General Approach

- **OBJECTIVE: Develop next generation *engineering* tools and methodologies with an order of magnitude improvement in accuracy.**

- **GENERAL APPROACH:**
  - Use validated high fidelity models and experiments to develop Reduced Models (RMs) of detailed behaviors.
  - *Embed* the RMs into coarser models of the entire engine

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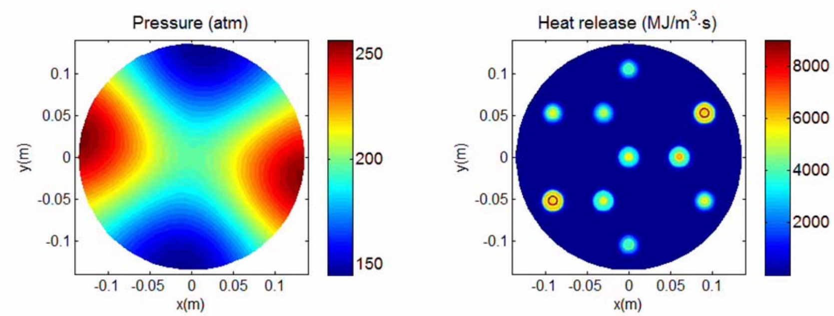
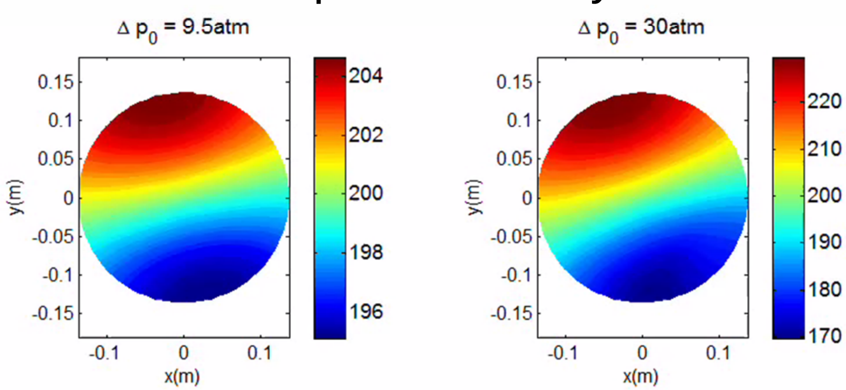
Example

- **AFOSR research by Sirignano, Sideris, Popov, Munipalli, Menon, and Kassoy**

Networks of fast but accurate simplified (reduced) injector models, trained off line, embedded as source terms in an overall "coarse" CFD



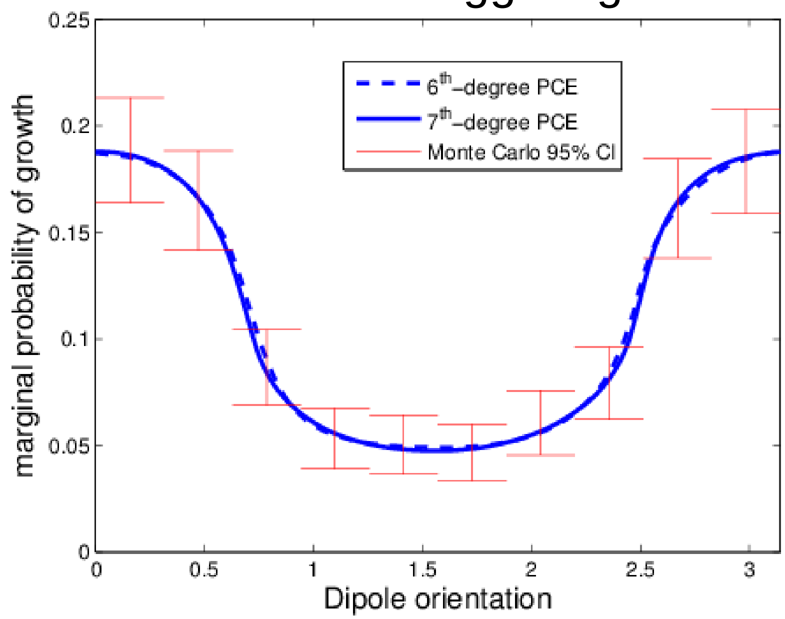
Low amplitude limit cycle 2T



Decaying 1T

Growing 1T

Stochastic triggering



Probability of triggering a 1T

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Technical Challenge

- **TECHNICAL CHALLENGE:**
  - MANY variants of how to implement the details of the general approach are possible
  - It is unknown at this time which will be successful
- **APPROACH:**
  - Don’t rely on any single implementation; invest in as many implementations as possible
  - Phase II will leverage relevant developments by CSTD and AFOSR, and be there to continue the work when those efforts end.

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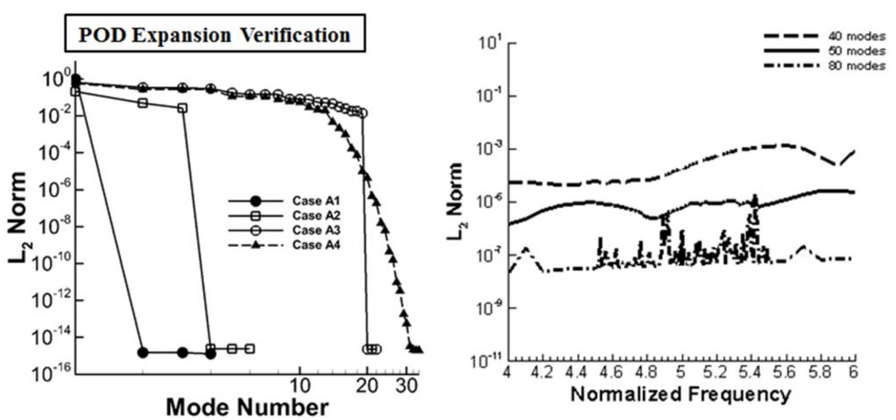
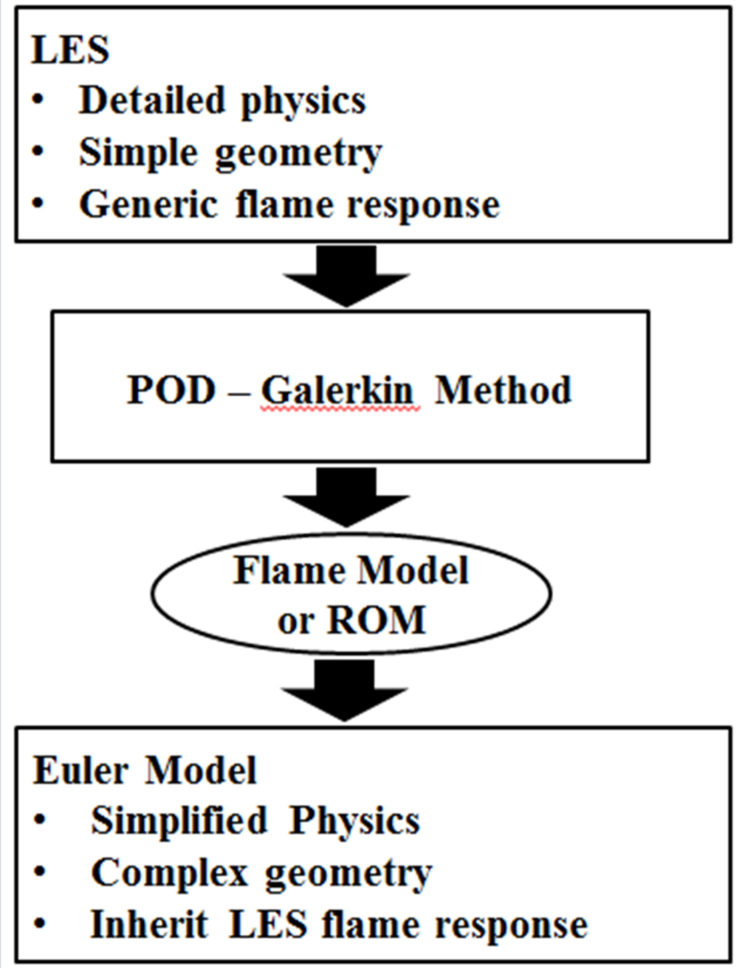
Purdue Approach

- **Investigate fundamental properties of POD-based RBMs**
  - Established reqd number of POD modes and training frequencies
- **Extension of POD-based RBM method to LES with chemical kinetics**





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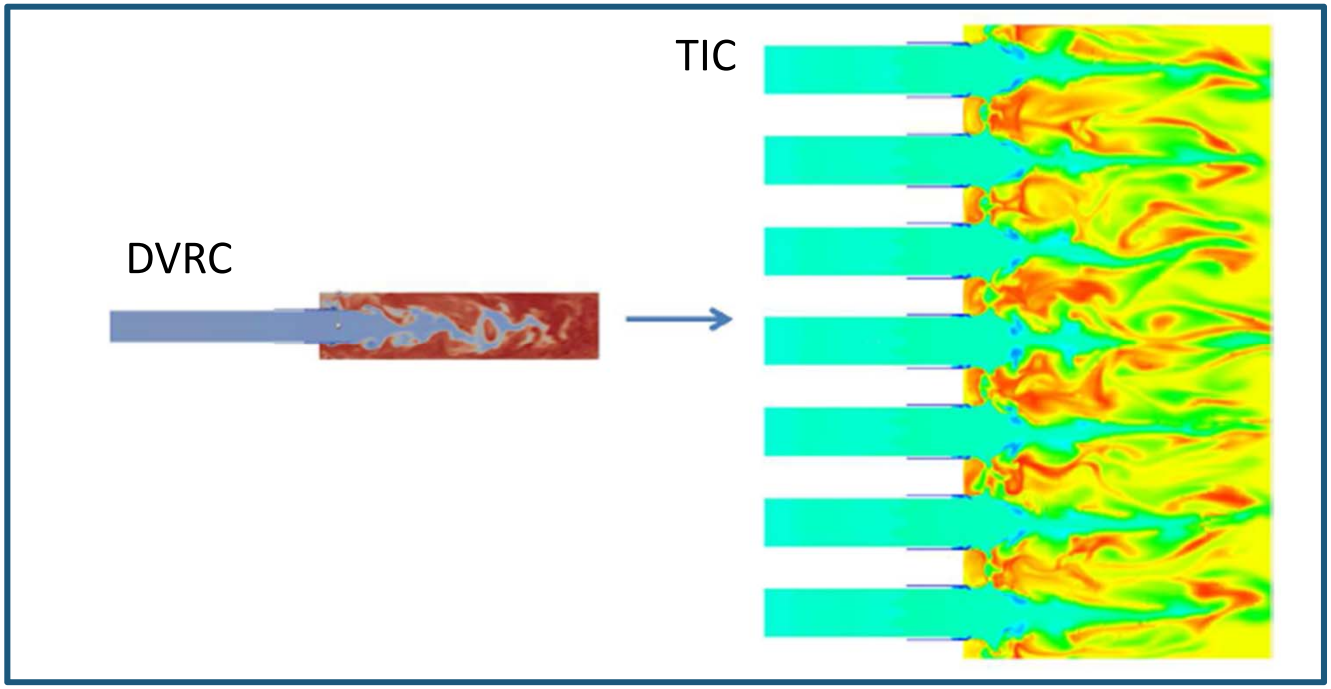
HyPerComp Approach

- **Develop multi-parameter RBM models for injectors trained using a single injector chamber (DVRC)**
- **Demonstrate "reusable" RBM surrogate models in a multi-injector context**
- **Deploy the RBM model above in a simulation of the Purdue TIC chamber**



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AFOSR Programs

- **Stay tuned**

Summary - Modeling

- **ALREST/VISP/CSTD**
  - ALREST has a suite of high-fidelity tools that are being validated by existing Purdue CVRC and TIC data (all methane).
  - The tools are being transitioned to production status by VISP.
  - VISP tools will support high-fidelity analysis of scaling methodology.
  - ALREST phase II will invest in Multifidelity Tools and Methodologies
  - CSTD will develop a SOA combustion stability software package called Stable Combustion of Rocket Engines (SCORE)
  - All CSTD tests to be accompanied by high fidelity modeling to understand the results and guide development

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Summary - Experiments

- **CaTS/CSTD/VISP**
  - CaTS formulated a scaling approach which informs the testing and the designs in CSTD.
  - CSTD and VISP expand the database initiated by previous AFRL and NASA efforts.
    - AFRL/TIC 1, NESC DVRC-1, *VISP/DVRC-2, VISP/TIC-2, CSTD/AFRL, CSTD/DVRC, CSTD/TIC, CSTD/10K, CSTD/40K, CSTD/GT Acoustics, CSTD/GT Methane, AFRL stability lab*

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